Galaxy Evolution

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Great Observatories Origins Deep Survey (GOODS)

- Basics:
  - Two fields: HDFN, CDFS
  - 320 sq arcmin (32 x HDFN)
  - Within ~ 0.8 mag of HDFN
- Instruments:
  - ACS, SIRTF, plus ground based (WFI/ESO, SOFI/ESO, ISAAC, CTIO/NOAO, KPNO, VLT, etc.)
  - Chandra
  - Bands: X-ray, U, B, V, R, I, J, H, Ks, *B, V, i, z, 3.6-8 microns, 24 microns,* and Radio

Recent Science

- Photometric Redshifts (Mobasher, Idzi, et al.)
- Lyman-break Galaxies $z \sim 4$ (Idzi, Somerville, Papovich, et al.)
- Comparison of galaxy models (Idzi, Somerville, Ferguson, et al.)
- ApJ Special Issue --- Fall?

Galaxy Evolution

- How and when galaxies formed stars, assembled their masses, and transformed into the range of morphologies observed locally?
- A complex and subtle problem:
  - many physical parameters depend on time (SFR, Mass assembly,…)
  - SFR regulated by many factors (gas cooling, line transitions, mergers, SNae)

Galaxies - Observables

- Information:
  - Spectrophotometric (Luminosity, Redshift)
    - Spectrum (flux vs. wavelength)
    - Photometry (broadband filter throughput)
  - Spatial (Morphology)

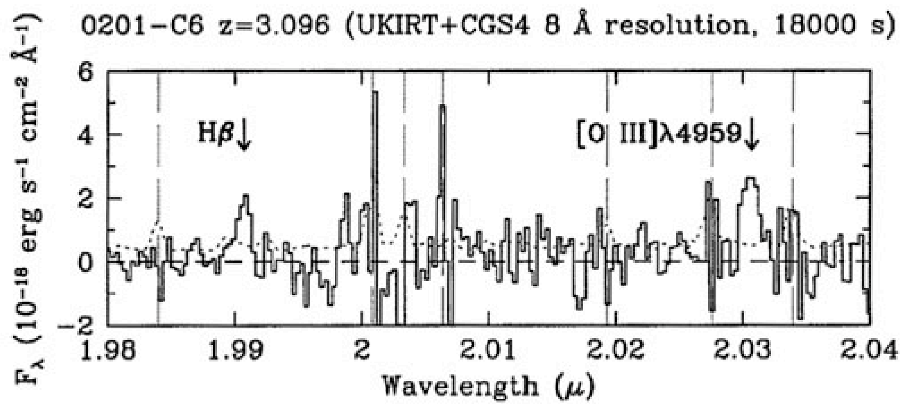
Galaxies - Physical Parameters

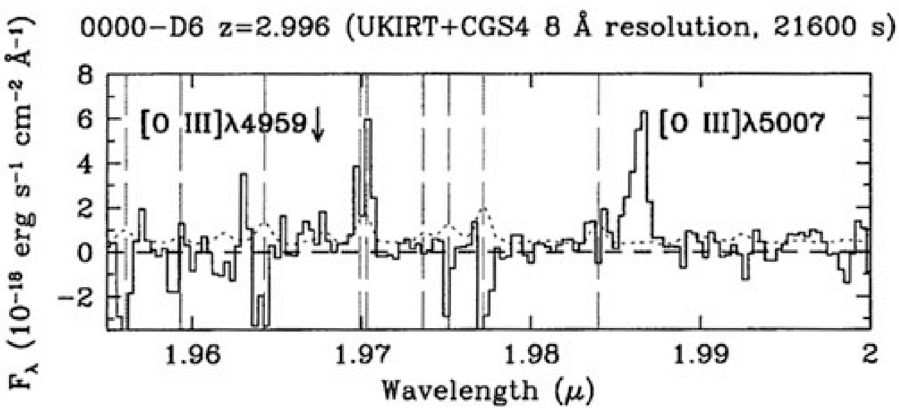
- Mass (Stellar, Dark), Age, Star Formation Rate (SFR), metallicity, dust, … (Stellar Populations)
- Morphology, size, Kinematics

Galaxy Evolution

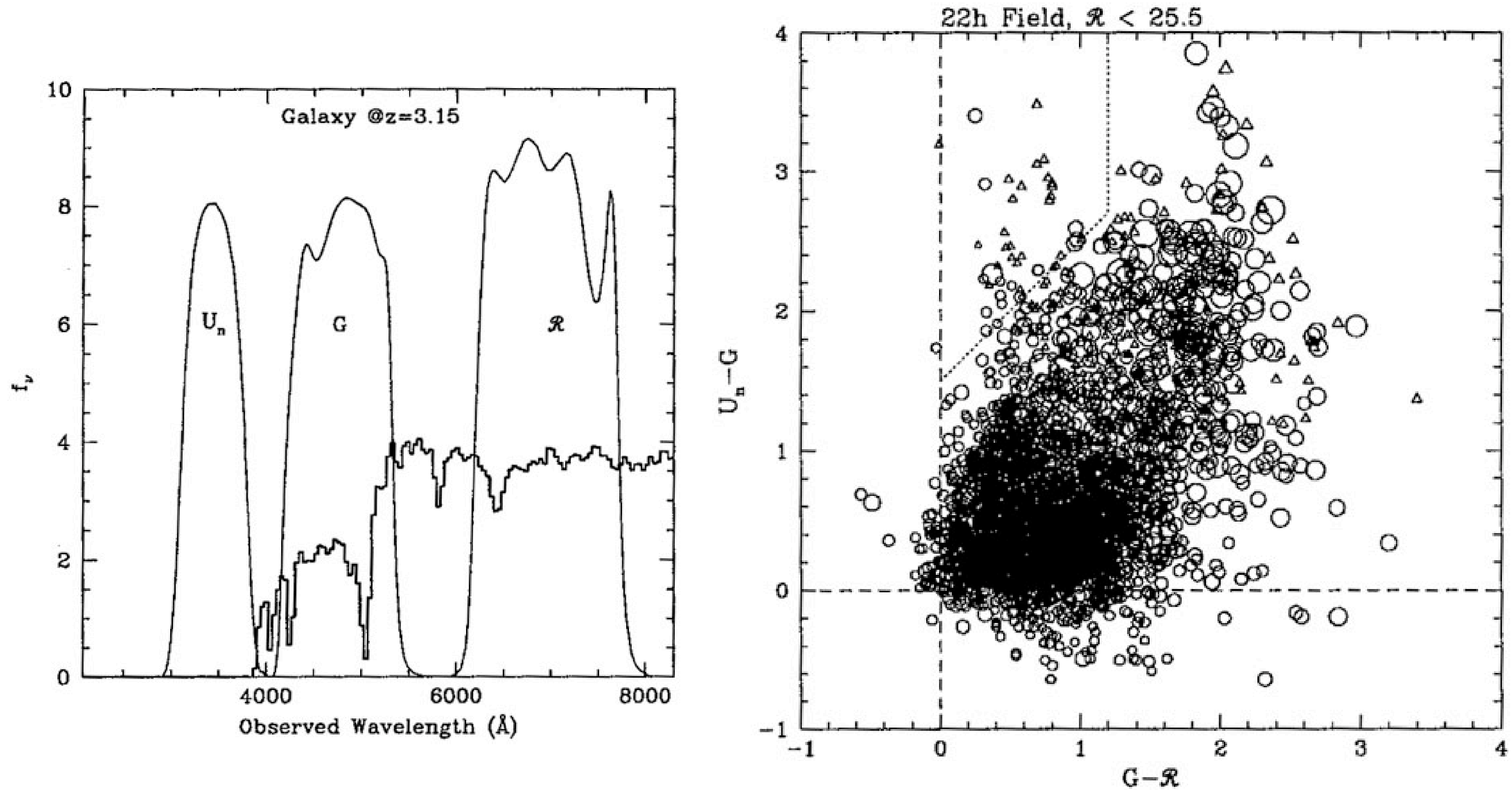
- Observational limits:
  – multiple components (stars, dark matter, gas)
  – spectroscopy expensive and limited
  – integrated light - young and old stellar populations
  – degeneracies (age-dust-metallicity)
  – additional selection effects

Spectroscopy

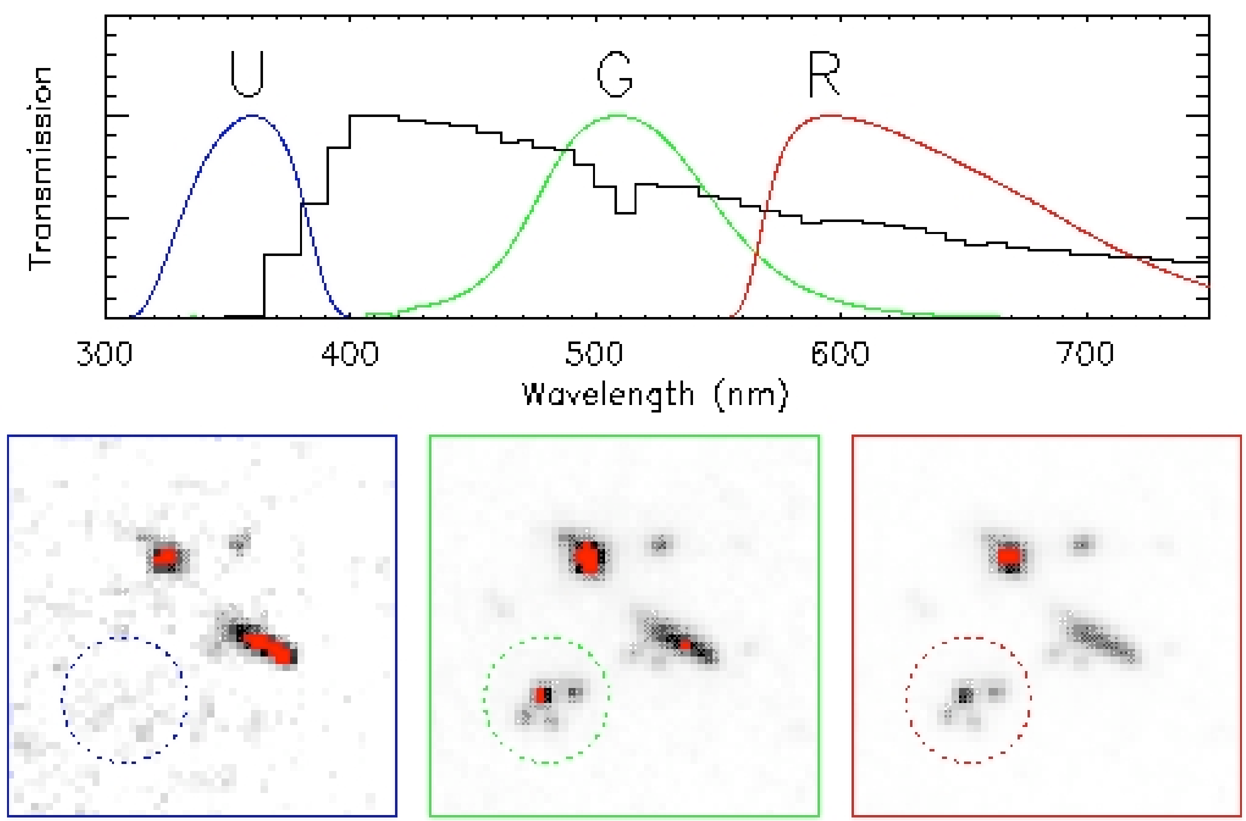




Lyman-break Technique



Lyman-break Technique



Traditional Approach

- Binned distributions of galaxies with their observables (L,z,color,morphology) compared to simplistic models
- Limited parameter space
- No confidence intervals

Qualitative!

Novel Approach

- Utilize multiple data set
- Test more complex models
- Quantitative constraints on parameters

Aim: given models and data compute the physical parameters (i.e. parameters with the highest likelihood values) -> Bayes' inference

Bayesian Approach

- CMB, photometric redshifts, CMDs, fundamental plane
- Probability as a measure of plausibility or the degree to which a given hypothesis is true based on the available data

Bayes' Probability

$P(\square_i|x) = P(x|\square_i)P(\square_i)/P(x)$

$P(\square_i|x) \quad P(x|\square_i)P(\square_i)$ $\{P(\square_i)$ all equal$\}$

$\square_i$ = {model: Mass,age,z,SFR,$\square$,metallicity,…}

$\square$ Backward (Local) and ab initio ($\square$CDM)

x = {data: photometry}

Issues

- Efficient parameterization
- Degeneracies (age-dust-metallicity)
  - Use orthogonal parameters
- Mergers
  - Strong affect on SFR
- Confidence intervals and calibration - computationally expensive

Monte Carlo Markov Chain (MCMC)

- Random walk in parameter space
- Future state depends only on the present state
- Properties: ergodicity, convergence, step size, mixing, …

MCMC

- To efficiently explore the likelihood space
  - Random draws from the posterior distribution that are a ‘fair’ sample of the likelihood space
  - Can estimate relevant quantities (mean, variance, confidence intervals)
  - Scales linearly with the number of parameters

MCMC

- After a ‘burn-in’ time - samples drawn from a stationary distribution
- Important considerations:
  - Step size
  - Ergodicity
  - Mixing
  - Convergence
  - Reparameterization (degeneracies, poor parameter choices)

Model Galaxies

- Use star formation histories from ΛCDM models and SSP to construct model galaxy SEDs (IMF, dust, □, z, …)
- Fold spectra through various filters, adjusting for redshift, to get ‘observed’ fluxes
- Look at number counts, LFs, and color-magnitude diagrams for various models
- Analyze via available statistical means (volume averaged SEDs, Bayes’ technique)
- In short: study the self-consistency and parameterization (calibration)

Simulation & Models

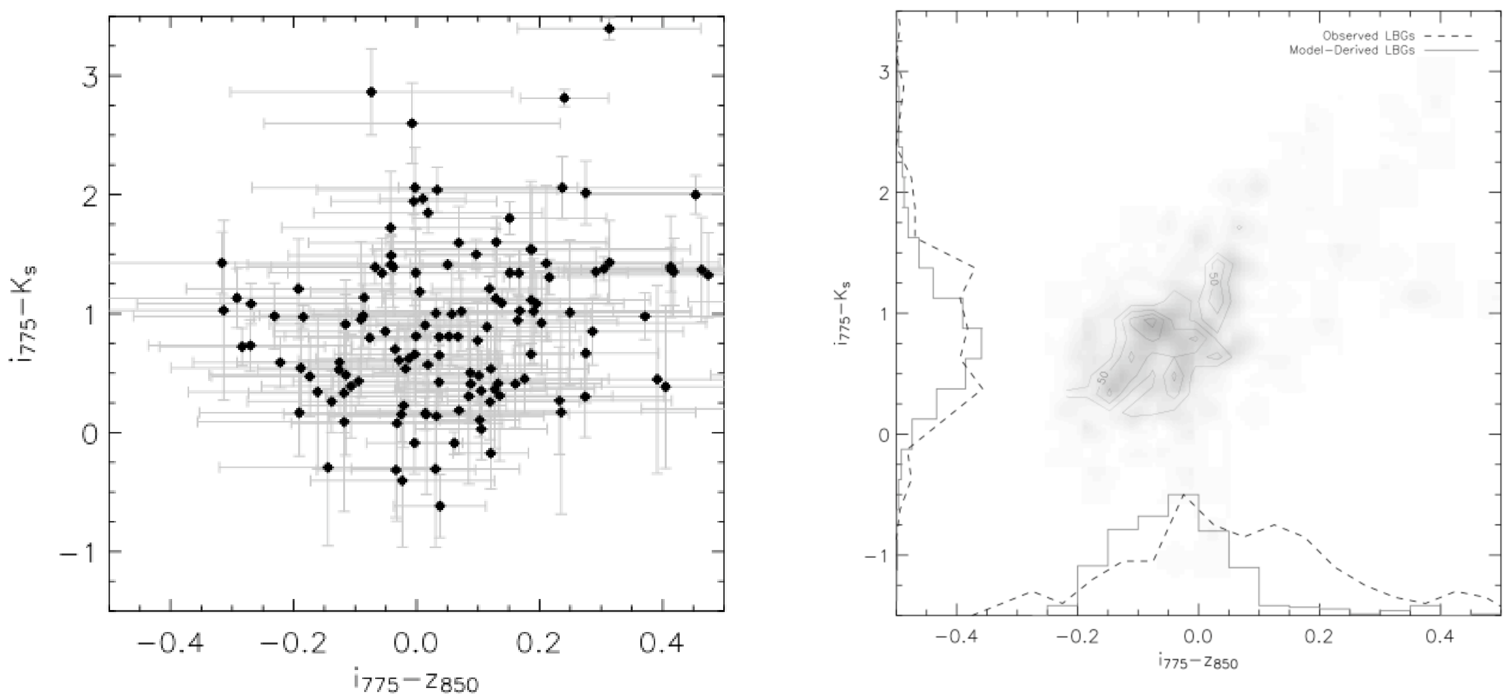
- SSP - single stellar burst with an exponential decay ($e^{-t/\tau}$)
  - $\tau \sim 10^6$ - bursty
  - $\tau \sim 10^{10}$ - constant
- Numerical and Semi-Analytic models
  - ΛCDM hierarchical structure formation
  - Gas cooling, star formation, mergers, SNae feedback, chemical enrichment, etc.

Early GOODS Science Results

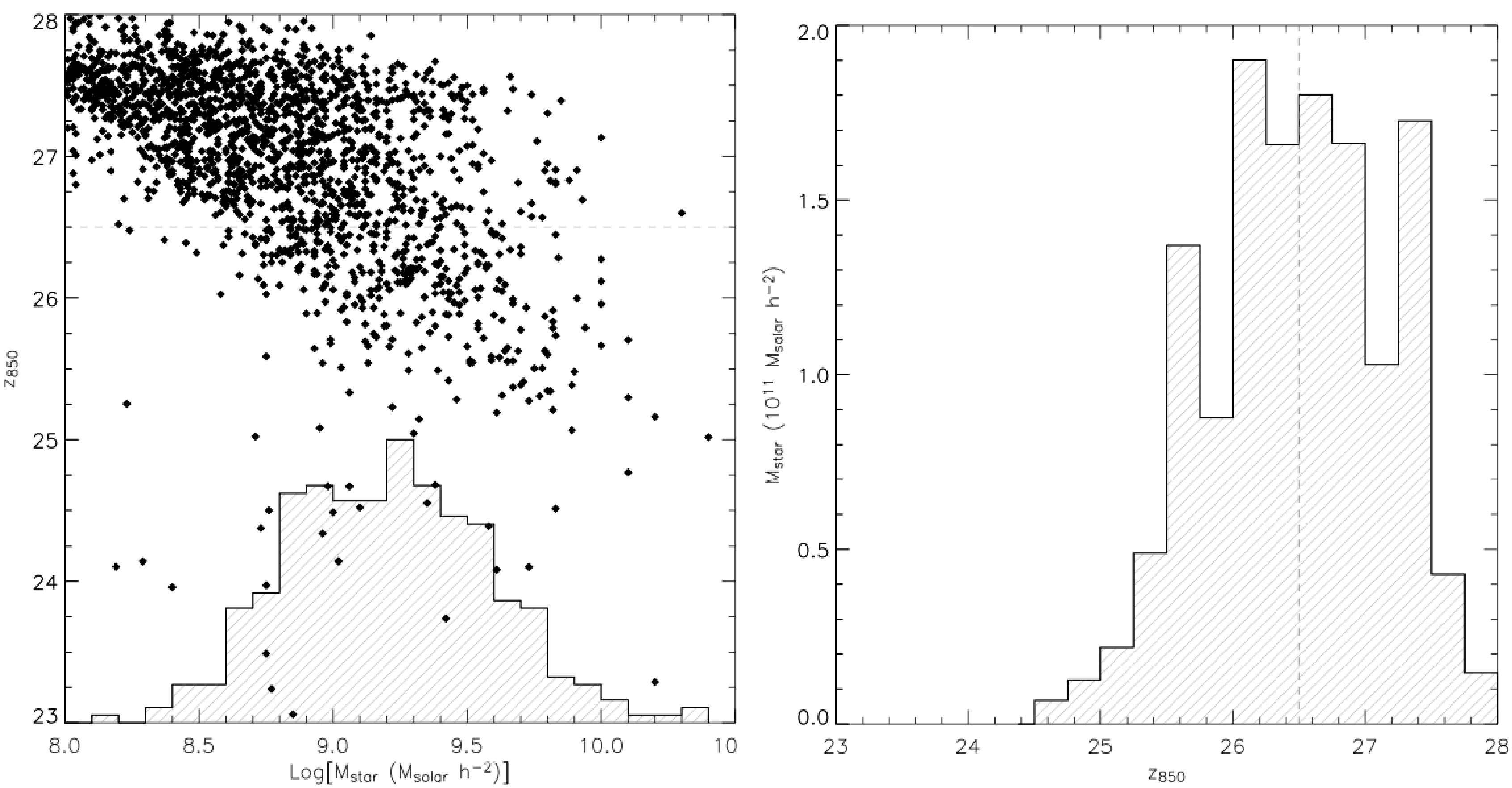
- Color-color comparison (i-K_s vs. i-z)
- Kolmogorov-Smirnov test: 19% vs. 10^{-8}
- Incompleteness test:
  - Semi-analytic model: 67%
  - Semi-empirical simulations: 73%
- LBGs at z ~ 3 and z ~ 4 near identical with modest evolution (SFR, Age, Mass, etc.)

Main Conclusions

- ~ 50% mass contained in UV-faint objects with $z_{850} < 26.5$ missed by optical surveys
- ~ 40% increase in mass of L^* galaxies (Papovich et al. - volume averaged SEDs)



Observed LBGs
Model-Derived LBGs
i775−Ks
i775−z850



z850
Log[Mstar (Msolar h−2)]
Mstar (10¹¹ Msolar h−2)
z850